Analysis of Staffing and Training Policies for a DSN Tracking Station

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This article presents a method for analyzing the effects of training and staffing policies, and for selecting optimum policies which minimize the expenditures for training and salaries while maximizing the performance of the tracking station. Two models have been developed which represent increasing levels of sophistication. The first characterizes steady-state behavior under the optimization of training, average capability, and crew size. The second, which is the dynamic model, optimizes the operating policy over a sequence of time segments. Each segment is characterized by a performance requirement (dependent on the phase of the mission), turnover, and training allocation with a corresponding change in average capability. With inputs such as required minimum station performance, training availability, current crew capability, and expected turnover, the output of the model will be the change in average crew capability, the percentage of time allocated for training, and the corresponding minimum cash expenditure for salaries and training.

I. Introduction

This article presents a methodology for analyzing the staffing and training requirements for operating a DSN tracking station. This analysis is part of a study made to develop tools to assist the management of the Deep Space Network in the planning and operation of the tracking stations.

In order to meet tracking commitments, the management of the tracking stations allocates personnel and financial resources among operations, maintenance, and training. Training is not only for new personnel and operators of new equipment, but also for upgrading the skills of veteran personnel. This article discusses the methods developed to assess the changing demands in these areas and to formulate an operating and training policy to satisfy requirements in a cost-effective manner.

Work is continuing, especially in the area of training effectiveness, to represent more characteristics of the staffing and training policy with our model, and to generate optimal training and staffing policies of practical value, using DSS 12 as the main example. The specific accomplishments expected in the near future from these efforts are listed in Section IX.

We begin with a discussion of the general features of the tracking station represented by our model.

II. Characteristics of the Model

(1) *Optimization of performance.* The performance of the tracking station in carrying out the different tasks may be measured by certain selected parameters. These parameters are treated as an output of the system, e.g., system availability, data recovery, number of data outages, etc. A maximization (or minimization) of one or more parameters provides the basis for the optimal operating policy.

(2) *Relationship between performance (output) and capability (skills available).* There exists a relationship between the capability of the men and the quality of the station performance, which in turn is explicitly related to the parameter being optimized. These relationships between capability and performance are ultimately expressed in quantitative terms.

(3) *Training to increase capability.* Training methods, which may be of varying effectiveness, are available to increase the capability of the men to perform their tasks. This may be either through increased proficiency in familiar subsystems or the development of proficiency in different or new subsystems.

(4) *Constraints.* There are constraints on the system, which are parameterized and which may vary with time. Typical constraints are the type of training methods available, the amount of time and manpower available for training, minimum performance requirements, and the number of crews required.

(5) *Costs associated with maintaining and improving performance.* These costs include operating expenses such as salaries, and some forms of capital investment such as training of new technicians.

These five features provide the basic structure and interrelationships for constructing the model. Within this basic framework, the model attempts to determine the "operating policy" which optimizes a given parameter while the tracking station is under a specified set of constraints.

III. The External Environment of the Tracking Station

The block diagram shown in Fig. 1 illustrates the relationships between the tracking station and its environment. The rectangular area within the dashed line represents the tracking station. The area outside the rectangle is the external environment of the tracking station. The significant relationships between the tracking station and areas in its external environment are identified.

Hiring is done to either add to, or replace, the people working at the station. The "world" represents the available manpower pool, and includes former employees.

The tracking station (the operating system) transforms the inputs into a tangible, measurable quantity. This is the output or performance of the system.

Two methods of training are considered, formal training and on-the-job training. The employees at the tracking station have the same general background, since they satisfy certain basic selection and hiring criteria. Thus, it is assumed in this model that the different training methods are equally effective for all employees. Further work is necessary to delineate the difference in the effectiveness of training by method, background of the individual, and the length of his employment at the tracking station.

IV. The Internal Environment of the Tracking Station

The people at the station may be divided into two categories:

(1) *Administrative personnel.* This category includes the station managers, secretaries, schedulers, etc., who perform the administrative tasks at the station.

(2) *Maintenance and operations personnel.* These include the operators and technicians who maintain and operate the station equipment.

Henceforth, for convenience, any reference to an individual at the station will imply an individual from category (2).

Station personnel, both new employees and veteran personnel, receive training to increase their operations and maintenance skills in various subsystems. As mentioned previously, two methods of training are considered: formal training and on-the-job training.

Formal training, as the name suggests, consists of classroom-type multimedia instruction. A group of trainees is taught a specific skill by a qualified instructor. Under the present Deep Space Network configuration, the Training Center develops, with the assistance of the Technical Staff, the instruction material and provides the instructors. During the time that a trainee is undergoing formal training, he cannot participate in station operations. Thus, the trainee performs no "useful work" during formal training, and all of his time is devoted to training.

On-the-job training takes place within the station. A trainee working with an already trained man acquires the necessary skills through observation and practice. Experience suggests that half the combined time of trainee and trainer results in useful work. The other half is devoted to learning, and consequently the process of on-the-job training is not as efficient timewise as formal training.

To express this distinction, we define the effectiveness of a training method to be the ratio of the time required to acquire the skill with the given method compared to a "standard" training method. For convenience, we take the more efficient formal training to be the standard. Experience suggests that trainees' time spent in on-the-job training is only 40% as effective as formal training (Ref. 1).

The operations and maintenance skills in different subsystems acquired by an individual through the process of training may be translated into a measure called the "capability" of the individual. The division of the tracking station into subsystems may be along hardware lines or along functional lines as is presently the case, with the number of subsystems ranging from 14 to 36. Henceforth, the use of the word capability will be restricted to the above definition.

The capability of an individual is measured in terms of the number of subsystems that he can operate and/or maintain. This measure is weighted by the relative difficulty factor of each subsystem, in the following manner (Ref. 2). The number of days of formal training required to train a man to operate and maintain a subsystem is determined. The capability of an individual is then determined by the subsystems that he can operate and maintain in terms of formal training days. If an individual has partial proficiency in a subsystem, the corresponding percentage of the total for that subsystem is added to his capability.

Between August 1971 and June 1972, DSS 12 was divided into 14 hardware subsystems. The average training time in a subsystem for operations and maintenance was 22 days ($\sigma = 15.6$) and 70 days ($\sigma = 42$), respectively. During this time period, the average individual capability varied between 191 and 241 days. Let

K_i = capability of the ith individual (formal training days)

K = average capability of the individuals in the station (formal training days)

N = number of men in the station

then

$$K = \sum_{i=1}^{N} \frac{K_i}{N} \tag{1}$$

For every "pass" (the continuous tracking period of a given spacecraft), the total amount of data available for collection can be determined from the spacecraft tracking and testing schedule. This total represents the maximum output of the system.

We define the data acquisition efficiency η = (actual data gathered/available data) for an average view period. The two factors which have the greatest influence on data acquisition efficiency (Ref. 3) are

(1) Capability of the station personnel

(2) Man hours spent in actual operations and maintenance (as opposed to training)

The men at the station are divided into several crews (1 to 4), depending on the number of shifts that the station operates. If the men are divided among the crews so that the total capability of the men in each crew, called crew capability, is the same for all crews, then

$\eta = f$ (crew capability, percentage of time spent in operations)

where

$$\text{crew capability} = \frac{NK}{M}$$

$$M = \text{number of crews}$$

and

$$1 \leq M \leq 4$$

Let

t_1 = fractional time spent in operations by the average individual

t_2 = fractional time spent in formal training by the average individual

t_3 = fractional time spent in on-the-job training by the average individual

Clearly,

$$t_1 + t_2 + t_3 = 1 \tag{2}$$

and

$$\eta = f\left(\frac{NK}{M}, t_1\right)$$

The data collected on station operations suggest an exponential relationship between capability and performance. This relationship exhibits the characteristic "knee" (Refs. 4, 5, 6) of learning curves, and a saturation effect:

$$\eta = 1 - \exp\left(\alpha_1 F_p \frac{NK}{M}\right) \qquad (3)$$

where

α_1 = exponential index

F_p = performance factor

We choose a value of $\alpha_1 = 0.0034$ on the basis of a best fit of the historical data.

To obtain a reasonable functional form for $F_p(t_1)$, we select the following empirical relationship based on historical station data:

$$F_p = \begin{cases} \sqrt{t_1} & 0.685 \leqq t_1 \leqq 1.0 \\ 1.2t_1 & 0 \leqq t_1 \leqq 0.685 \end{cases} \qquad (4)$$

This relationship is a reflection of the fact that the station can devote up to 20% of its man hours to training before operations begin to be seriously affected. The effect of t_1, for $\alpha_1 = -0.0034$, on data acquisition efficiency η is shown in Fig. 2. Recall that $(1 - t_1)$ is the fractional time spent in training.

V. Identification of Costs

Our model is based on the cost equation

$$CVL = CH + CA + CF + CS + CT + CP \qquad (5)$$

where

CVL = overall cost

CH = hiring cost

CA = cost of attrition

CF = cost of overhead personnel

CS = cost of salaries of operations personnel

CT = cost of training

CP = cost of lost performance

Salaries:

CF = average salary of administrative personnel times number of administrative personnel;

$$CF = 12 \times 3 = 36 \text{ (\$K/year)} \qquad (6)$$

$$CS = CK \times N \qquad (7)$$

where

CK = average salary of an individual of capability K;

$$CK = \frac{8 + K}{50} \text{ (\$K/year)} \qquad (8)$$

This linear relationship between capability and salary fits some recent, randomly selected data fairly well (Ref. 7).

Hiring and attrition:

CH = cost of hiring one man (= \$500) times number of men hired

CH = 0.5 × number of men hired (\$K/year)

CA = cost of termination processing of one man (= \$50) times number of men that leave

CA = 0.05 × number of men that leave (\$K/year)

Training costs:

CT = cost of training = cost of formal training + cost of on-the-job training

$$CT = N \times CS\,(\alpha_2 \times t_2 + t_3) \qquad (9)$$

α_2 = formal training cost factor = 2 (being twice as expensive as on-the-job training on a per-trainee-hour basis, since extra costs such as lecture preparation and instructor training must be included). This factor is determined by analysis of historical cost and operating data from the Technical Staff and Training Center.

Performance is a benefit, but one way of quantifying it is in terms of lost performance. Lost performance can be considered either in terms of inefficiency or lost data. For one optimization policy, we need to parameterize lost data by assigning a value to the available data. This value of the available data is dependent on the mission, its phase, and competing priorities (Refs. 3, 8). The cost of lost performance, expressed in \$K/year, may be expressed by the following linear relationship:

$$CP = (1 - \eta) \times \text{value of available data (\$K/year)} \tag{10}$$

Since the optimal policies will be in the range of η greater than 80%, the assumption of linearity in the range 80% to 100% will be adequate. If one were interested in values of 50% and lower, nonlinear factors, which describe the penalty of poor performance, might have to be introduced.

VI. Optimization Technique

Figure 3 is a detailed representation of the station operating system shown in Fig. 1. Optimization occurs at two points (Refs. 9, 10):

(1) Distribution of time between operating and training

(2) Distribution of training time between formal and on-the-job training

The allocation of time between the two methods of training and operating can be optimized according to one of the following policies:

(1) Minimization of the cash expenditure (CE), subject to a required minimum data recovery efficiency constraint, where cash expenditure is

$$CE = CH + CA + CF + CS + CT \text{ expressed in \$K/year}$$

(2) Minimization of the overall cost (CVL), which includes the value of lost data:

$$CVL = CE + CP$$

Turnover is treated as an independent parameter (external constraint), either as an absolute number or as a percentage of the total number of men in the station.

For convenience of illustration, we have considered the average capability of those that leave to be the same as the station average, and that of people who are hired to be zero. This assumption is in accord with past experience, but the model does have the flexibility to specify other values of capability for the departing individuals and the new hires. This implies that whenever there is turnover, new hires will have to be given training to maintain the average station capability.

VII. The Steady-State Model

For this model, we assume that the station requirements and crew capabilities do not change with time. The dynamic model will address the problem of changing capability due to turnover and training.

The steady-state requirement implies that the number of people hired equals the number that leave and that the new hires are brought up to the average capability through the process of training. For convenience of illustration, we make the following additional assumptions:

(1) The time period is 1 year, consisting of 250 working days for each man.

(2) There are three crews ($M = 3$).

The following examples illustrate the typical results which can be obtained with the steady state model.

A. Minimum Cash Expenditure to Obtain a Required Efficiency

In this example, the operating policy is obtained as a result of minimizing the cash expenditure CE. For a 20% annual turnover, Fig. 3 shows the cash expenditure required to provide a minimum data recovery efficiency. This relationship is provided for a family of values of station size (N) and average individual capability (K).

Station size varies from 15 to 36, which corresponds to crew sizes of 5 to 12. A crew size of 5 is typical of the current staffing at DSS 12 under the operating philosophy of a central console and "operations engineers." (Refs. 11, 12, 13). A crew size of 10–12 was typical at DSS 12 in 1970 and is also typical of the larger stations, like DSS 14.

Average individual capability is considered from 50 to 200 days. Though some individuals have capability greater than 200 days, the average is unlikely to exceed that value. Thus, 200 days is used as the upper bound. In each figure, the comparisons of N and K which provide the maximum information are illustrated.

In Figure 4, values of K above 95 are bunched closely together, which indicates that increasing capability does not increase efficiency for constant N. The reason is obvious. At high turnover and high capability, most of the time is spent in training to regain the lost capability rather than in operations. Curves for $N = 15$ to 18 terminate at the point corresponding to $K = 200$.

The policy of specifying a minimum required data recovery efficiency is close to the present spacecraft project procedure. It is interesting, however, to perform a more global optimization by trading off the cost of maintaining a station of high performance capability against the cost of lost data resulting from poor performance. The following examples illustrate this second optimization policy.

B. Effect of Crew Size on Minimum Overall Cost

Turnover of three men/year (ν) and a data value of \$1200K/year (\$) are considered in Fig. 5, where the minimum overall cost is plotted against average individual capability.

For average capability less than 150 days, a station size of 21 is optimal. Between 155 and 175, a station size of 18 men is optimal. For average capability greater than 175, the optimal station size is 15 men. In general, with increasing capability a smaller station size is indicated.

The data value of $\$ = 1200$, 1.2 million dollars per year, is somewhere between what one might choose for the cruise and extended mission phases of a recent Mariner-type spacecraft (Ref. 3).

C. Effect of Data Value on Crew Size

With turnover of three men/year, the station sizes which minimize the overall cost are plotted as a function of average individual capability, in Fig. 6. These curves help to quantify the intuitively obvious relationship (basically inverse) between station size and average capability. The curve for $\$ = 600$ turns around at $K \simeq 40$ days, indicating that it is not desirable to operate the station with average capability less than 40 days.

In Fig. 6, for an average individual capability of 120 days and a data value of \$600K/year, a station size of 16 men is indicated. When the data value is increased to \$1800K/year, the optimal station size increases to 25 men for the same *average individual capability*.

D. Minimum Cost and Optimal Capability Contours

Figures 7 and 8 show contours of minimum overall cost and optimal capability, respectively. The turnover is 30% of station size (N) instead of an absolute number, as in the previous case.

Figures 7 and 8 may be used in conjunction to determine the station's "operating point."

For a particular data value, either the station size or average individual capability must be selected as the starting point. Since there are greater constraints on station size than average individual capability, it is suggested that data value and station size be used as the starting point. Figure 7 then gives the minimum overall cost, and Fig. 8 provides the optimal average individual capability. If the present average individual capability is lower than the optimal, training will be required to achieve the optimal level. It must be remembered that these operating points are dependent on the assumed annual turnover, and in Figs. 7 and 8 it is 30%.

If data value is chosen at \$2M/year and a station size of 27, the minimum overall cost, from Fig. 7, is \$460K/year and the optimal average individual capability, from Fig. 8, is 128 days.

In all of the above exercises, the optimal data acquisition efficiency and training policy are determined by the model as a result of the optimization.

So far, we have seen how a wide range of information about station operation may be obtained by using the steady-state model. However, the use of the steady-state model imposes two restrictions:

(1) There is no net change in station capability.

(2) An averaged value is used for available data.

The dynamic model, which is an extension of the steady-state model, overcomes both of these difficulties.

VIII. The Dynamic Model

The dynamic model exhibits the effects that changing data values, average capability, and turnover have on operating policy. The total time span is divided into a sequence of segments, with each segment, or stage, characterized by

(1) Individual terminations with immediate replacement

(2) Average individual capability at start of the time segment

(3) Average individual capability at the end of the time segment, which is dependent on the turnover and training policy during the time segment

(4) Available data value (used with the policy minimizing overall cost CVL)

Station size N is constant through all segments.

The other inputs are

τ = duration of each stage

T = number of stages considered

The steady-state model, considered in the preceding section, is actually a particular case of the dynamic model with τ = 1 year and T = 1, and no change in capability.

The dynamic model provides an operating policy, resulting from optimizations based on an anticipated demand (data value profile or required minimum efficiency) under specified constraints. The operating policy, and more specifically, the training policy, is a reflection of the overall long-term needs of the station rather than the effect of one stage alone. This is the essential difference from the steady-state model. For example, an extremely high data value (or required minimum efficiency) in stage 6 may influence training policies through stages 3 to 5, as in training in preparation for a launch. Let

η_t = data acquisition efficiency in stage t

CVL_t = overall cost in stage t

$CVLT = \Sigma CVL_t$ = sum of the overall cost in each stage

CE_t = cash expenditure in stage t

$CET = \Sigma CE_t$ = sum of the cash expenditure in each stage

Three different versions of the dynamic model are used to deal with different optimization requirements and constraints:

Dynamic Model 1

Optimization: Minimize $CVLT$

Constraints: Training availability in each stage

Dynamic Model 2

Optimization: Minimize $CVLT$

Constraints: Training availability in each stage
Minimum required efficiency in specified stages

Dynamic Model 3

Optimization: Minimize CET

Constraints: Training availability in each stage
Minimum required efficiency in each stage

The minimization is based on a dynamic programming technique (Refs. 14, 15), proceeding in the forward direction. The dynamic program has T stages, which are the ends of the time segments. The state variable is the average individual capability. The boundary condition, or starting point, is the initial average individual capability at the station K_0.

Starting from K_0, there is a maximum and minimum average capability that can be achieved in any stage. This corresponds to 100% formal training and no training, respectively, and is an inherent constraint on the average individual capability.

Sample results from Dynamic Model 1 and Dynamic Model 2 are presented to illustrate the workings of the models.

Sample results from Dynamic Model 1 are illustrated in Figs. 9 and 10. A time span of 1 year is considered, divided into four stages, each of 3 months' duration.

Station size N is 30 men, and there are no constraints on training. There is no turnover during the entire time span.

In this example, the data value increases to \$2M/year in the fourth stage. Starting from an initial value of 20 days, the average individual capability levels off at 90 days. The bulk of the training is done during the first stage, when the data value is lowest, with no training in the fourth stage.

The data acquisition efficiency obtained as a result of minimizing the total overall cost $CVLT$ is plotted in Fig. 10. The overall cost and cash expenditure per stage are also shown. The total cash expenditure $\simeq$ \$250K.

Sample results from Dynamic Model 2 are shown in Figs. 11 and 12. Station size N is 27 men, and there are no constraints on the quantity or type of training in any stage. A time span of 2 years is considered, divided into eight segments of 3 months each.

The data value profile is a sawtooth type having a value \$2000K/year in stages 2, 4, 6, and 8 and \$0K/year in the other four stages. A sawtooth data value profile is selected, since it is typical of missions. Missions are characterized by periods of high tracking requirements (launch, orbit insertion), separated by less demanding phases, such as the cruise phase.

The initial average capability K_0 is 20 days.

There is a minimum efficiency constraint in stages 6 and 8. The efficiency in both of these stages must exceed 99%, corresponding typically to launch or encounter phases.

The turnover profile was generated by sampling from a Poisson distribution. The turnover through stages 1 to 8 is 3, 5, 7, 7, 2, 1, 5, 2 men, respectively. This is 81% and 37% turnover for the 2 years, respectively.

It is desired to find the operating policy to minimize the total overall cost *CVL* under the given constraints and input conditions.

Maximum capability increases to 200 by the end of stage 5 and levels off, since, in practice, individuals seldom exceed this by much.

Minimum capability decreases gradually (due to turnover) to a level of 15 and then jumps to 160 in the sixth stage. This is the effect of a minimum efficiency constraint of 99% in stage 6. A capability of less than 160 would result in the minimum efficiency constraint being violated.

The optimal capability increases, through training, to reach 160 days at the start of the sixth stage. Training follows a sawtooth pattern which is a complement of the data value profile.

In Fig. 12, the actual efficiency in stages 2 and 4 is influenced by the data value in those stages. However, in stages 6 and 8, the minimum efficiency constraint is clearly the dominating influence. The actual efficiency, in general, has a profile similar to the data value, a conclusion which is not unexpected.

The overall cost and cash expenditure through the stages are also shown in Fig. 12. The cash expenditure in stages 1, 3 and 5 is high because of the training costs (100% training in each stage). The cash expenditure averages to $450K/year.

Thus, the dynamic model provides an estimate of the demands that are placed upon the station, in terms of training and cash expenditure, to assist in formulating an operating policy which will meet future commitments.

IX. Further Efforts

We are presently in the process of applying this analysis to the recent developments at DSS 12, and expect to report on the following specific items:

(1) Statistical relationship between salary and capability (based on the new subsystem breakdown which became effective in July 1973)

(2) Analysis of the capability lost during the actual attrition process

(3) Analysis of the relationship between the qualification and certification program at DSS 12 and our method of measuring capability

(4) Measures of past station performance which can be related to crew capability

We are also developing a distributed capability model which will be able to optimize the allocation of individuals at the station to crews and training programs. A preliminary report of some of this work has been given in Refs. 1 and 3.

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Table 1. Definition of Symbols

Symbol	Definition
α_1	Exponential index
α_2	Formal training cost factor
η	Data acquisition efficiency, %
η_t	Data acquisition efficiency in stage t
ν	Number of men leaving/year, men/year
τ	Duration of each stage, months
$	Value of available data, $K/year
CA	Cost of attrition, $K
CE	Cash expenditure, $K
CE_t	Cash expenditure in stage t, $K
CET	Sum of cash expenditure in each stage, $K
CF	Cost of overhead personnel, $K
CH	Hiring cost
CK	Salary of an individual, $K
CP	Cost of lost performance, $K
CS	Cost of salaries of operations personnel, $K
CT	Cost of training
CVL	Overall cost
CVL_t	Overall cost in stage t, $K
$CVLT$	Sum of overall cost in each stage, $K
F_p	Performance factor
K	Average capability of individuals in the station, days
K_0	Initial average individual capability
M	Number of crews
N	Number of men in the station
P	Number of states in dynamic program
T	Number of stages considered
t_1	Fractional time spent in operating
t_2	Fractional time spent in formal training
t_3	Fractional time spent in on-the-job training

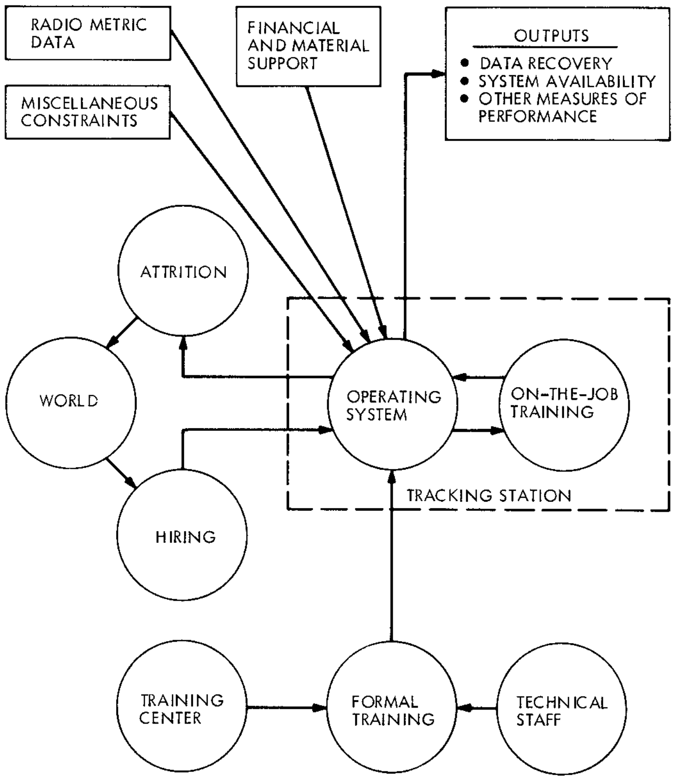

Fig. 1. The tracking station and its environment

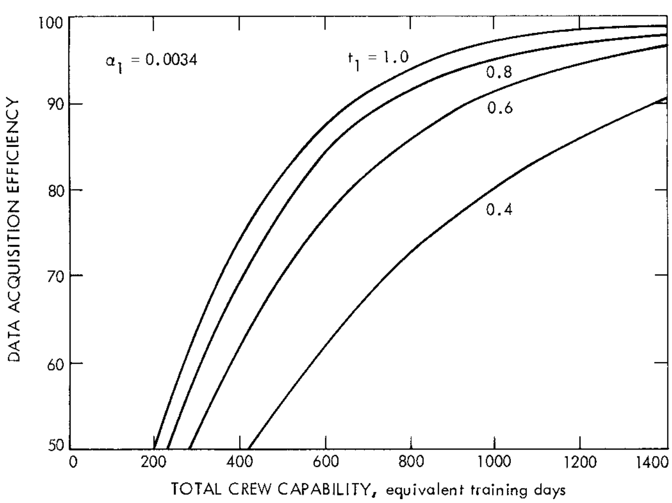

Fig. 2. Effect of training on data acquisition efficiency

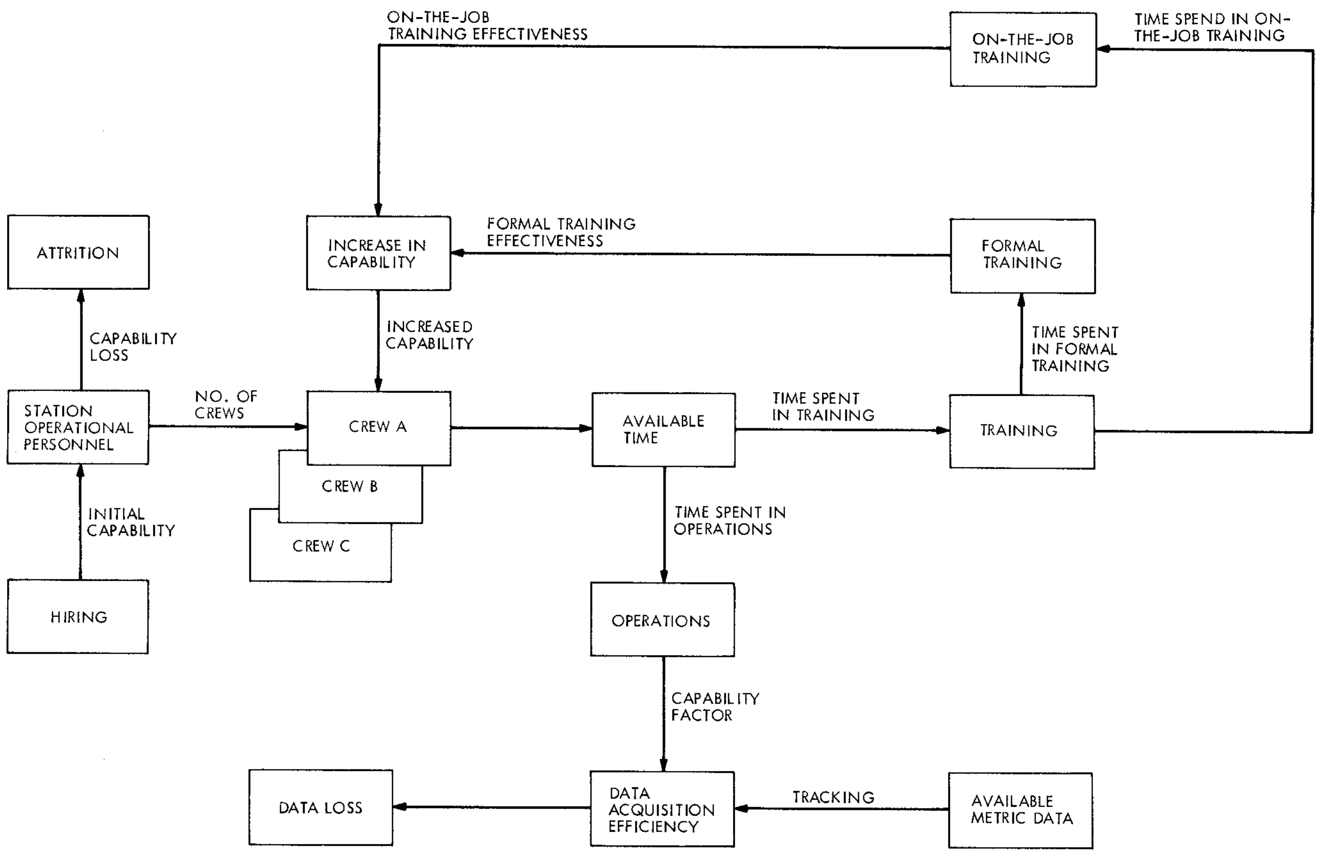

Fig. 3. Station dynamics

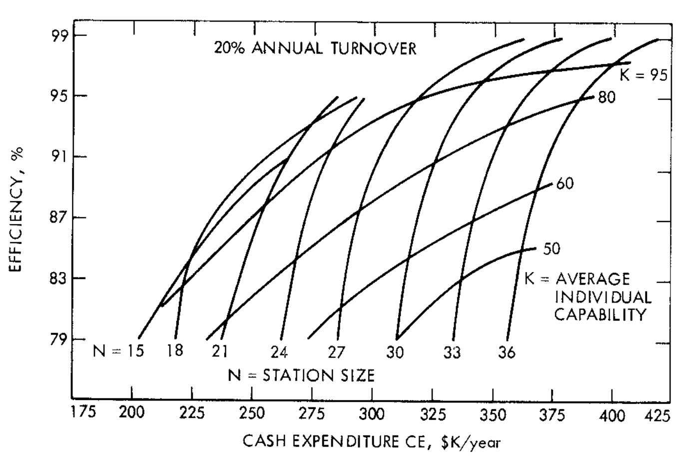

Fig. 4. Capital expenditure for data acquisition efficiency

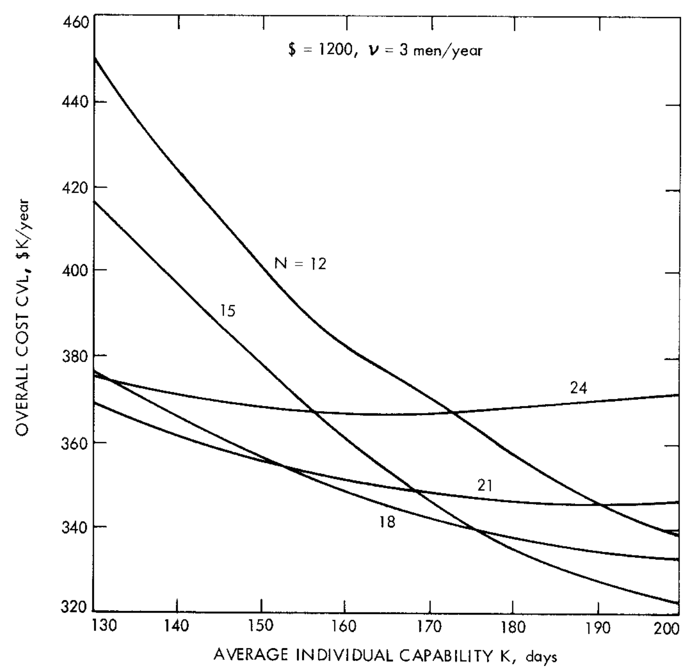

Fig. 5. Effect of crew size on overall cost

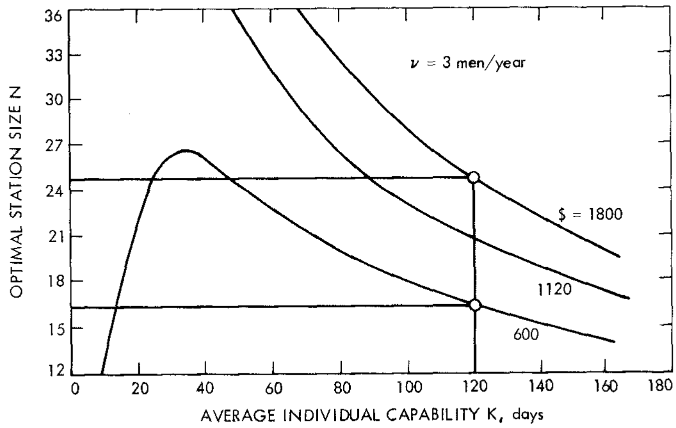

Fig. 6. Effect of data value on crew size

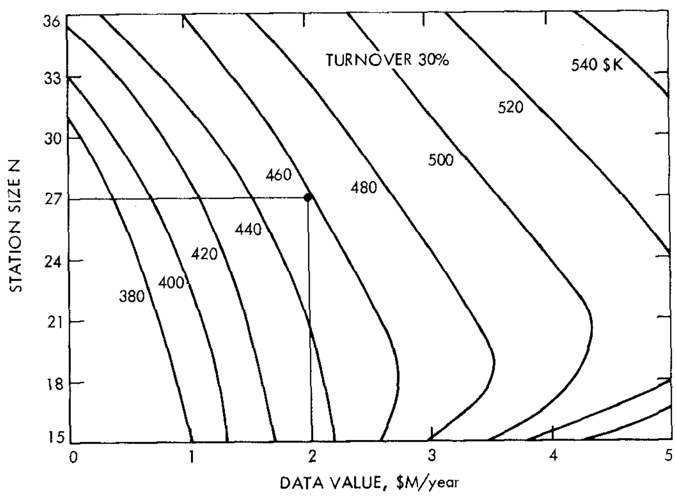

Fig. 7. Minimum overall cost contours

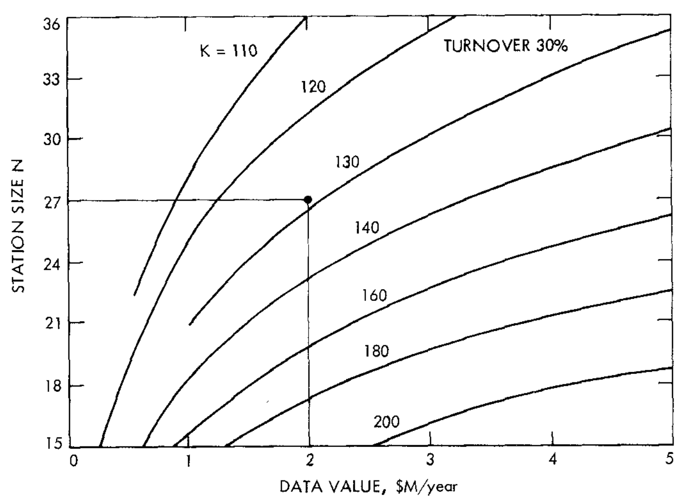

Fig. 8. Optimal capability contours

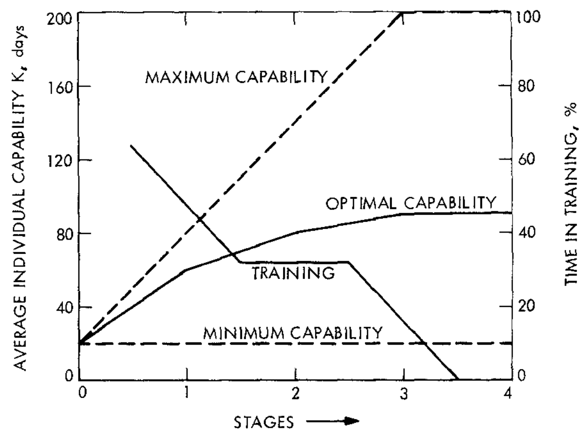

Fig. 9. Training and optimal capability

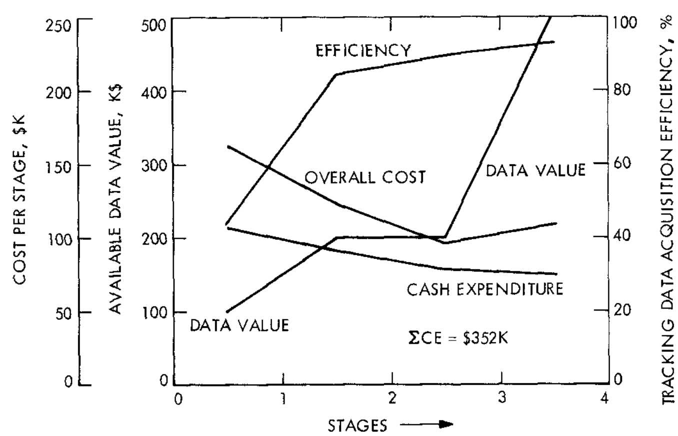

Fig. 10. Cost and efficiency

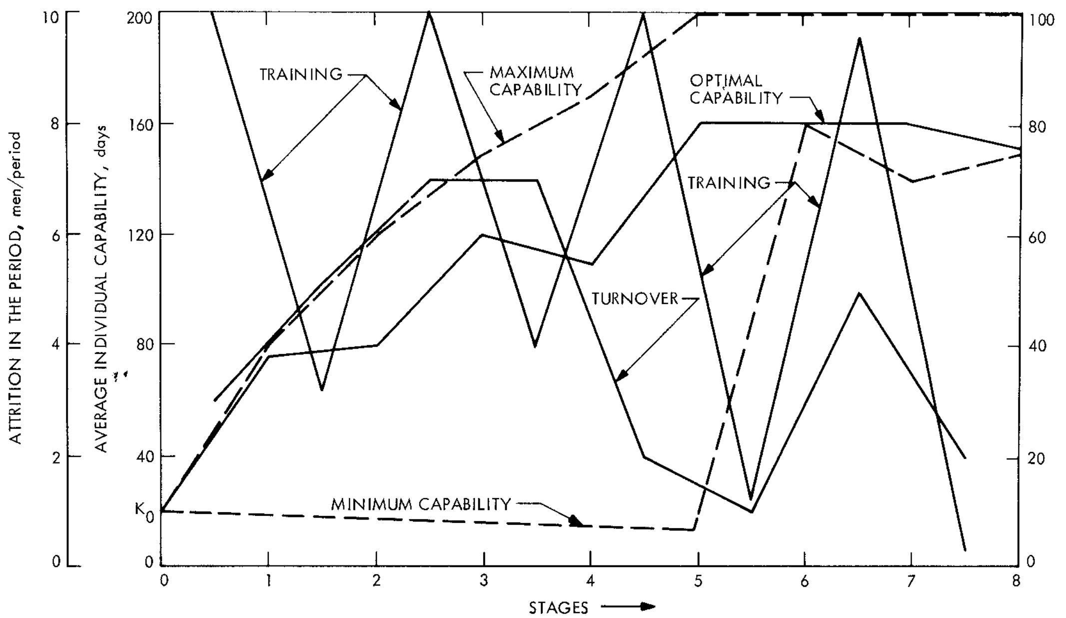

Fig. 11. Training and optimal capability

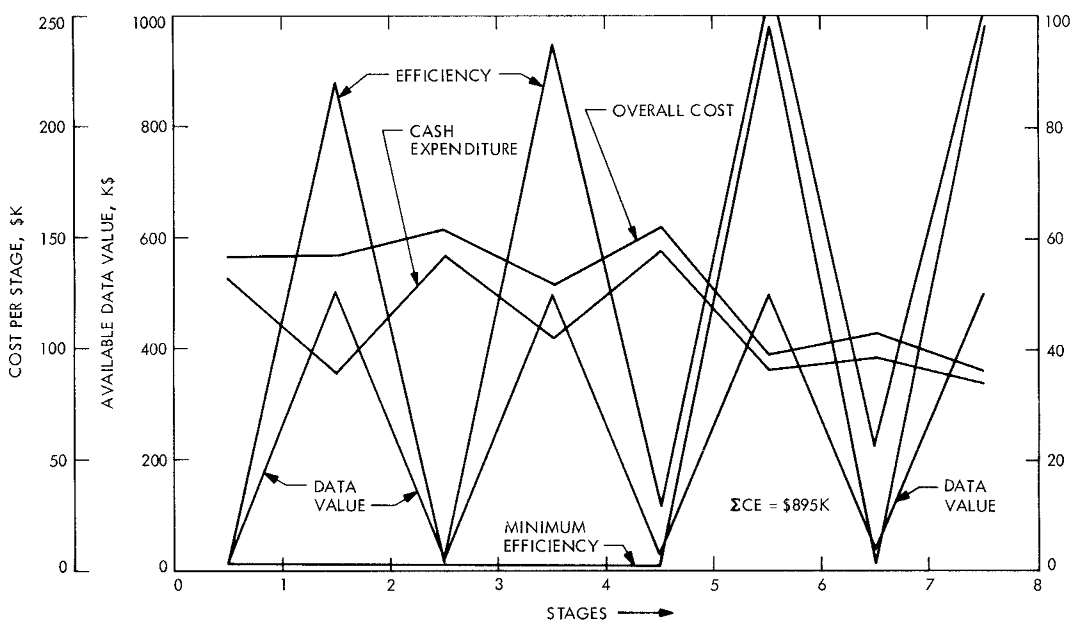

Fig. 12. Cost and efficiency